Evaluating Sieve Tray Flooding in A Distillation Column Using Kister and Haas; and Fair's Correlations

Awajiogak . A. Ujile* and John T. Iminabo
Rivers State University of Science & Technology, Department of Chemical/Petrochemical Engineering, PMB 5080, Port Harcourt, Nigeria.Tel: +2348033398876; ujile.awajiogak@ust.edu.ng; +2348039499000; iminabo.john@ust.edu.ng *Corresponding Author.

Abstract

This research project evaluates the problem of flooding in a distillation column that uses sieve tray. Data obtained from a typical crude oil refining company in Nigeria were used in the various calculations using the Kister and Haas; as well as the Fair's correlations. The flooding capacity of the column and its effect on the fractional hole area, hole diameter and tray spacing of the column were determined. The flooding capacity was determined as 0.104 m/s and 0.121 m/s for the two correlations. The flooding capacity has a directly proportional relationship with the tray spacing TS and fractional hole area of the column but has an inversely proportional relationship with the hole diameter of the column. Results obtained have shown that the Kister and Haas; and Fair's correlations experienced 46.38 % and 51.3 % flooding respectively. These results have shown that the performance of the column is below capacity utilization.

Keywords: separation efficiency, downcomer, sieve tray, froth entrainment.

Introduction

A common problem that can occur in distillation columns is flooding. A typical distillation column is filled with a structured packing, showing the liquid flow and vapor flow when the column is operating normally. Liquid flows downward over the structured packing countercurrent to the upward flowing vapor. The vapor must follow a tortuous path; but, the void space in the packing is predominantly filled with vapor. The vapor is said to be the "continuous phase". The upward flow of the vapor exerts an "aerodynamic drag" on the falling liquid. This drag force acts in opposition to the force of gravity and slows the flow of the falling liquid Emerson, (2014). When the relative flow rates of the vapor and liquid are such that the drag force is greater than or equal to the gravity force; then, the liquid stops flowing down the column. This condition is called flooding. Flooding can begin at any vertical location in the column.

The excessive accumulation of liquid inside a distillation column due to flooding has negative impact on the maximum capacity of the column. It also leads to sharp increases in column differential pressure and significant decrease in separation efficiency. The problem of flooding affects product purity and thus the economics of production is severely affected. The issue of flooding is therefore a concern to distillation column operators, plant designers and indeed chemical engineers.

In evaluating distillation column performance, American Institute of Chemical Engineers (AIChE) Equipment Testing Procedures Committee considered the following parameters for the testing: whether column performance meets vendor guarantees; identify capacity bottlenecks; troubleshoot performance problems; determine operating range of the column; define optimum operating conditions; develop basic data and correlations for new designs; calibrate computer simulations for use in optimizing, bottlenecking, and design studies, CEP AIChE, 2013. The work of Chevemisinoff, (2000) showed jet flooding from high vapor rates which formed liquid seal at the top of the column. This brought about poor separation efficiency and poor product quantity and purity. T he test procedure carried out here was on alcohol solutions of commercial interest such as ethyl, methyl and isopropyl alcohol solutions. At the end of their analysis it was reported that Isopropyl alcohol did not suffer flooding. Kister (1992), explained that flooding is caused by one of the following mechanisms: spray entrainment flooding; froth entrainment flooding; down -comer malfunctions and large diameter columns defects. Details of the mechanism can be obtained from the literature cited.

Plate efficiency plays an important role in the design of distillation column. For the desired separation of mixtures to be achieved in a distillation process, the vapor leaving a plate in the column must be equal to the liquid leaving that plate. Therefore, the actual number of plates required for a particular separation duty is determined by the efficiency of the plate. This implies that any factor that causes a decrease in the efficiency of plate will definitely change the performance of the column. So, it is important to determine the efficiency of plate column before carrying out the actual construction/installation of distillation column for separation of mixture of crude oil in the refinery. By so doing, it is possible to separate crude oil mixtures that will yield the required product purity Ujile and Amagbo (2013).

Souders and Brown (1934) theoretically analyzed entrainment flooding in terms of a droplet settling velocity. According to their analysis, flooding occurs when the upward vapor velocity is high enough to suspend a liquid droplet, giving rise to the equation below:

$$U_{S\text{'},\ \text{flood}} = C_{SB}\sqrt{\frac{\rho_L-\rho_G}{\rho_G}} \qquad (1)$$

From Equation 1, the Souders and Brown flooding constant, C_{SB} can be defined as:

$$C_{SB} = U_{S\text{'}}\ flood\ \sqrt{\frac{\rho_G}{\rho_L-\rho_G}} \qquad (2)$$

Where $U_{s,flood}$ is flooding velocity(m/s), C_{SB} is the flooding capacity factor (m/s), $\rho_L = Liquid\ density$ kg/m^3,$\rho_G = Vapour\ density$ kg/m^3

The Fair flood has been the standard of the industry for entrainment flood prediction and was recommended by most designers Van (1967), Holland (1981) . C_{SB} is a function of the flow parameter $F_{LV,}$ tray spacing TS, surface tension σ, and fractional hole area A_h. C_{SB} is based on the net area A_N, and is evaluated from figure 1.
The flooding vapor velocity is calculated from the equation;

$$U_{N,\ \text{flood}} = C_{SB}\left(\frac{\sigma}{20}\right)^{0.2}\sqrt{\frac{\rho_L-\rho_V}{\rho_V}} \qquad (3)$$

The Kister and Haas Correlation is a recent correlation for entrainment flooding prediction presented as follows:

$$C_{SB} = 0.144\left(\frac{d_H{}^2\sigma}{\rho_l}\right)^{0.125}\left(\frac{\rho_G}{\rho_L}\right)^{0.1}\left(\frac{S}{h_{ct}}\right)^{0.5} \qquad (4)$$

h_{ct} is the clear liquid height at the transition from the froth to spray regime, based on the Jeronimo and Sawistowski (1973) correction as modified for physical properties by Kister and Haas (1990).

Another methods for predicting froth entrainment flooding was presented by Kister et al (1994). Most of the work reported in the literature lumps spray and froth regime entrainment flooding together. Froth entrainment flooding is far less common than spray entrainment flooding and occurs mainly at close (< 18inch) tray spacing, when the froth envelope can approach the tray above. Some flood data at close tray spacing that pertains to froth entrainment flooding were reported in Mayfield et al (1952). Froth regime entrainment work is also relevant to froth entrainment flooding Chatterjee, (1973).

The factors affecting froth entrainment flooding differ from those affecting spray entrainment flooding. The critical variable is the distance between the top of the froth and the tray above this implies that the flood velocity strongly increases as tray spacing is raised, liquid load is lowered and weir height is lowered Smith (1963).

Some flood and entrainment data confirms this trend Mayfield et al (1952), Friend et al (1960). On the other hand tray geometry variables such as hole diameter and fractional hole area can be expected to have a lesser effect (if any) on froth entrainment flooding. This was confirmed by entrainment data but not by flood data Friend et al (1960), Kister and Haas (1990).

Froth entrainment can be predicted using the Fair or Smith (1963) correlations. Both included froth entrainment flood data in their data base. Testing of Fair's correlation against a handful of more recent data suggests that it gives conservative froth entrainment flood predictions Chatterjee (1973), Smith (1963). The Smith et al correlation is claimed to be less conservative. The Kister and Haas correlation is unsuitable for froth entrainment flood predictions, Smith (1963) .

Critical analysis of the above researchers' work shows the following limitations for Kister and Haas Correlations:

1) At pressure above 150 psia, downcomer flood is often the capacity limitation. This limitation is not predicted by the correlations.

2) At high liquid loads (above 7-10 gpm) in downcomer flood is often the capacity limitation.

3) At lower tray spacing, entrainment flooding may be related to lifting of the froth envelop and to froth rather than spray height.

4) Clear liquid (water) height at transition from froth to spray regime (h_{ct}) $_{water}$ expression does not apply for liquid loads lower than 0.5 gpm of weir (Eq. 7)

It is therefore imperative to improve on the work of previous researchers by introducing the following fundamental principles:

1) Making calculations based on operating data from the typical crude oil refinery in Nigeria to quantitatively demonstrate flooding mechanism.
2) Emphasizing on the distillation tray malfunctions (flooding, weeping, etc), causes and troubleshooting techniques for solving these problems. Discriminating between flooding and dumping mechanisms.

For sieve trays, the entrainment flooding point can be predicted by using the method of Kister and Haas. The method is said to reproduce to a large database of measured flood points to within ±15 percent.

$$C_{SB,flood} = 0.0277(d_h^2\sigma/\rho_L)^{0.125}(\rho_G/\rho_L)^{0.1}(TS/h_{ct})^{0.5} \quad (5)$$

Where, d_h= hole diameter, mm; σ= surface tension, mN/m (dyn/cm) ; ρ_G ,ρ_L = vapour and liquid densities, kg/m^3;TS= tray spacing, mm; h_{ct}= clear liquid height at froth to spray transition, mm; h_{ct} is obtained from the equation:

$$h_{ct} = h_{ct,H2O}\left(\frac{996}{\rho_L}\right)^{0.5(1-n)} \quad (6)$$

$$h_{ct,H2O} = \frac{0.497A_f^{-0.791}d_h^{0.833}}{1+0.013Q_L^{-0.59}A_f^{-1.79}} \quad (7)$$

$$n = 0.0091d_h/A_f \quad (8)$$

In equation 7, $Q_L = m^3$ liquid down flow/(h.m weir length) and A_f = fractional hole area based on active (bubbling) area; For instance,

$$A_f = \frac{A_h}{A_a} \quad (9)$$

The Fair's correlation for decades has been the standard for the industry for entrainment flood prediction. It uses a plot of surface tension corrected Souders and Brown flood factor C_{SB} against the dimensionless flow parameter shown in Fig.1. The flow parameter represents a ratio of liquid to vapor kinetic energies.

$$F_{LG} = \frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} \quad (10)$$

Low values indicate vacuum operations; high values indicate operation at higher pressures or at high liquid/vapour loadings. The liquid/gas ratio is based on mass flow rate. For multi pass trays, the ratio needs to be divided by the number of passes. The strength of the correction is at the low flow parameters. At higher flow parameters, (high ratios, high pressures and emulsion flow) Fig. 1 gives excessive conservative predictions, with the low values of C_{sbf} to the right likely to result from downcomer flow restrictions rather than excessive entrainment. The curves may be expressed in equation form as,

$$C_{sbf} = 0.0105 + 8.127\ (10^{-4})\ (TS^{0.755})\ \exp\ (-1.463\ F_{Lv}^{0.842}) \quad (11)$$

where TS = Plate spacing, mm and the equation for gas velocity is expressed as;

$$U_{nf} = \left(\frac{\sigma}{20}\right)^{0.2}\left(\frac{\rho_L-\rho_G}{\rho_G}\right)^{0.5} \quad (12)$$

Where U_{nf} = gas velocity through the net area at flood, m/s ; C_{sbf} = Capacity parameter corrected for surface tension, m/s. Experimental values have been correlated against a dimensionless flow parameter F_{LG} as shown in Fig. 1. The flow parameter represents a ratio of liquid to vapor kinetic energies as shown in Eq. 10.

This research therefore involves:

Quantitative determination of flooding mechanism of a column using trays; and identifying the distillation tray malfunctions (flooding, weeping, etc), causes and troubleshooting techniques for solving these problems.

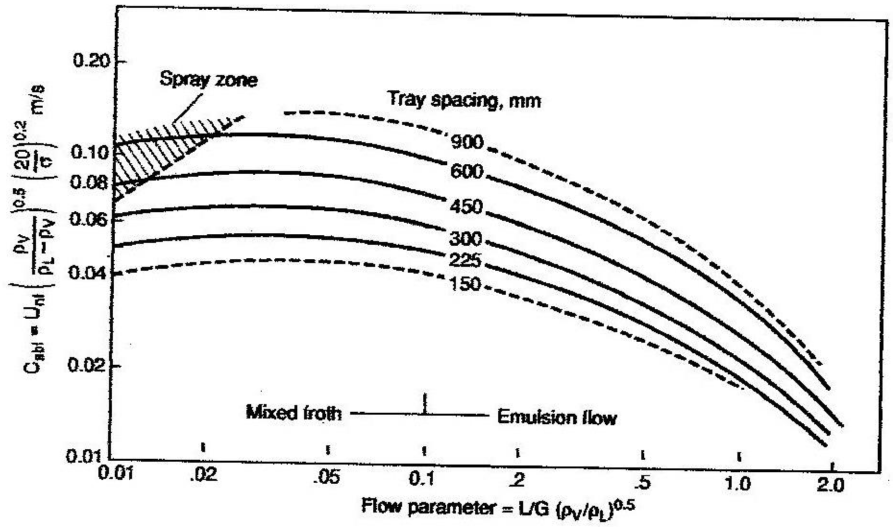

Fig. 1: Fair's entrainment flooding correlation for columns with crossflow trays (sieve, valve and bubble cap). Perry, (2008) Chemical Engineers Handbook

Methodology

A distillation column that uses sieve tray of 2.591m diameter was considered for the separation of liquefied petroleum gas (propane/ butane mixture). Physical properties data obtained from a typical Refinery Company, in Nigeria for LPG Merox unit distillation column is tabulated below:

TABLE 1 Physical properties data for crude oil LPG Merox Unit

Key Dimensions of the Tray column	
column cross section, m^2	5.27
down comer area, m^2	0.6324
net area, m^2	4.64
active area, m^2	4.00
hole area ,m^2	0.4
hole diameter, mm	5
weir length, m	1.916
weir height, mm	50
tray spacing , mm	900
Condition and properties at the top tray	
Temperature, ^{0}C	76.5
Pressure, kg/cm^2	18
Vapour flow, kg/h	15,334
Vapour density, kg/m^3	0.523
Liquid flow, kg/h	26,327
Liquid density kg/m^3	582
Surface tension, mN/m	12.46

Data obtained from a typical crude oil refinery company

The methods employed in predicting flooding capacity in this research project is the Kister and Haas method and the Fair's correlation method. Both methods are proposed by Perry, (2008). These methods are utilized to evaluate, and compare the flooding capacity for a distillation column.

Kister and Haas gave a correlation which is said to reproduce a large data base of measured flood points to within + 15 percent. CSB, flood is based on the net area.

Here equation 5 becomes relevant and h_{ct} was obtained subsequently from equation 6.:
The assumed system (Derating) Factor (SF) for the crude tower is 0.85 (Perry 2008)

For Kister & Haas

$$\% flood = 100 \times \frac{C_{SB}}{C_{SBderated}} \tag{13}$$

Fair's Correlation

$$\% flood = 100 \times \frac{\mu_N}{SF \times \mu_{Nflood}} \tag{14}$$

$$Q_L = \frac{L}{\rho_L \times h_w} \tag{15}$$

Substituting the values from the plant data, we obtained h_{ct} = 13.496 mm, $C_{SB,}$ flood = 0.104 m/s
Similarly, applying FAIR'S correlations the following values were obtained, F_{LV} = 0.05147; $C_{SB\ flood}$ = 0.133 m/s and % flood = 51.3 % .
Considerations of the relationship between C_{sb} and some design parameters:

Relationship between C_{sb} and Fractional hole area A_f

Fractional hole area, A_f is the ratio of hole area and active area.
Taking all other terms in equation 13 as constants and varying only A_f. Working with a range of A_f = 0.05 to 0.08, and substituting it into equation 13 these values were obtained for C_{sb} the results shown in Tables 2, 3 and 4 as well as figures 2, 3 and 4 respectively were obtained.

Table 2: Values for C_{sb} and A_f

A_f	C_{sb}
0.05	0.05
0.06	0.051
0.07	0.0515
0.08	0.0525

Relationship between C_{sb} and Tray Spacing TS

Taking all other terms in equation 13 as constants and varying only values for TS (900 to 2000mm) and substituting same in equation 13, the following values were obtained for C_{sb}

Table 3: Values for C_{sb} and TS

TS	C_{sb}
900	0.07
1000	0.074
1100	0.079
1200	0.081
1300	0.085
1400	0.088
1500	0.091
1600	0.094
1700	0.097
1800	0.1
1900	0.1
2000	0.104

Relationship between Csb and hole diameter.

Similarly equation 13 shows that C_{sb} varies with d_h according to the following equation,

$$C_{sb} = \frac{0.12}{d_h^{\,0.1}} \qquad (16)$$

Substituting values for d_h into equation 16 starting from d_h = 5 mm to 40 mm gives the following values for C_{sb}

Table 4: Values for C_{sb} and d_h

d_h (mm)	C_{sb}
5	0.1
10	0.095
15	0.092
20	0.089
25	0.087
30	0.085
35	0.084
40	0.083

Results and Discussions

Effect of flooding capacity on tray spacing and productivity

As shown in Table 3 and Fig 3, C_{SB} rises with tray spacing. Roughly, C_{SB} is proportional to the tray spacing to a power of 0.5 to 0.6. At low tray spacing (<15 in), the power may be somewhat higher due to the proximity of the froth envelope and/or excessive splashing from the dispersion at the tray. As flooding capacity rises owing to increase in tray spacing, it leads to a low degree of distillate product purity thereby resulting in low productivity.

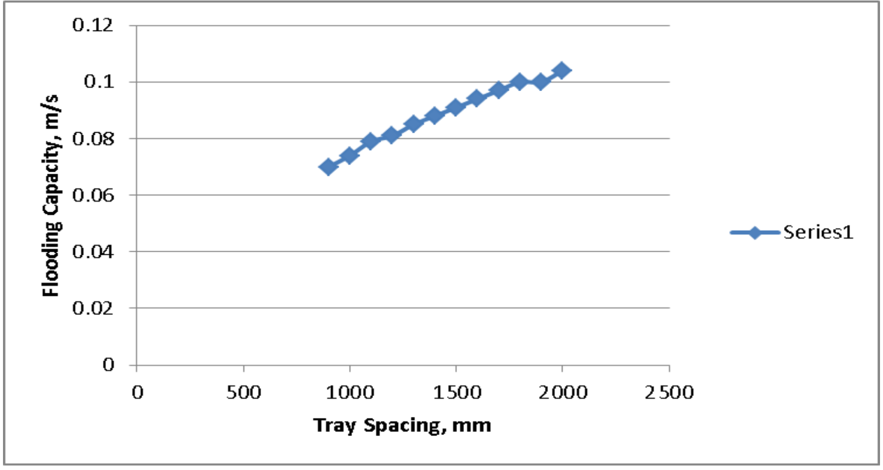

Fig.2: Graph of Flooding Capacity (m/s) against Tray Spacing (cm)

Effect of Flooding Capacity on Fractional Hole Area and Productivity:

From Table 2 and Fig 3 C_{sb} increases with fractional hole area. Roughly when fractional hole area is between 0.05 and 0.08, an increase in fractional hole area of the order of 0.01 will enhance C_{sb} by about 5% as also stated by Lemieux and Scotti (1969). When the fractional hole area exceeds 0.1, the rate of increase of C_{sb} with hole area is substantially lower Stichlmair (1978), Kister (1990). The flooding capacity which rises with fractional hole area reduces the degree of distillate product purity which amounts to low productivity of the distillation column.

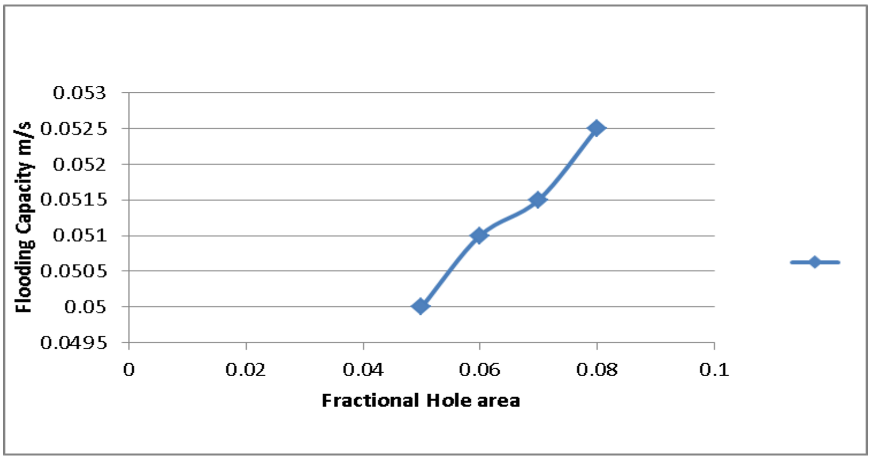

Fig 3: Effect of Flooding Capacity on Hole Diameter

As shown in Table 4 and Fig 4 C_{SB} increases as hole diameter is reduced. Roughly C_{SB} increases with the reciprocal of hole diameter to a power of 0.1 to 0.2 Kirachbaum (1969), Kister and Haas (1990).

The flooding condition fixes the upper limit of vapour velocity. A high vapour velocity is needed for high plate efficiencies and the velocities will normally be between 70 to 90 percent of that which would cause flooding. For design, a value of 80 to 85 percent of the flooding velocity should be used.

C_{SB} is practically independent of pressure in distillation systems Gerster et al (1942). This suggests that C_{SB} is, at the most, only a very weak function of physical properties. Since the relationship between the flooding capacity and hole diameter is an inverse relationship, so this effect increases the product purity hence increasing distillation column productivity.

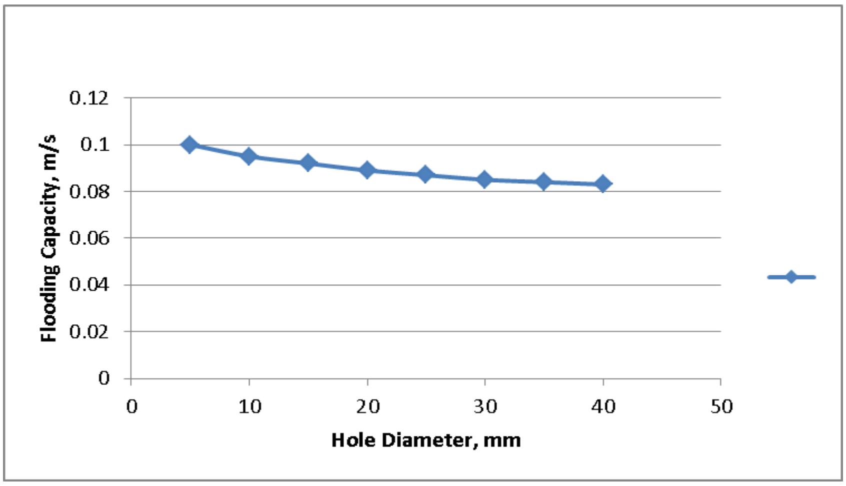

Fig. 4: Graph of Flooding Capacity (m/s) against hole diameter (mm)

Conclusion

Distillation Column Flooding is a phenomenon that can cause loss of separation and negatively impact in the performance and energy efficiency of the distillation process. The onset of distillation column flooding is associated with a change in the flow regimes of the gas and liquids flowing inside the column.

This work has been able to detail causes of flooding and its effect on the performance of the column. The basic calculation guideline on how to evaluate flooding capacity of a column is established. The evaluation has been able to highlight the following significant areas:

(i)Flooding, types and methods of predicting flooding (ii) Causes of flooding (iii) Operating problems arising from flooding (iv) Methods of trouble shooting flooding (v) Effects of flooding on the production capacity of a distillation column for typical Crude oil Refinery in Nigeria.(vi) Calculation of the flooding capacity.

In this project, flooding applicable only to the sieve tray distillation column was considered. The flooding capacity based on the Kister and Haas correlation was determined to be 0.104m/s, while the derated C-factor at flood should be 0.088. Percentage flooding using Fair's correlation is 51.3%, while that using Kister and Haas correlation is 46.3%.

However, for the system since the calculated percentage flooding is less than 80% it is advised that the column diameter be reduced. This is because from literature for an effective design and operation the percentage flood is determined to be from 80% and above. The low value of the percentage flood indicates that the column is under-utilized.

References

Branan, C.R. (1978) *The Fractionator Analysis Pocket Hand Book*, Gulf Publishing Co.
CEP, AIChE Publication, June 2013, Evaluating Distillation Column Performance p 27.
Chatterjee, N. (1973) *Paper Presented at the AIChE Meeting* New Orleans
Chevesmisinoff, N. P. (2000): Handbook of Chemical Engineering Processing Equipment.Butterworth – Heinemann, Woburn, M. A
Emerson Process Management. http//www.rosemount.com assessed on 24 April 2014.
Friend, et al (1960) *Chemical Engineering* 31 (21), P 57
Gerster, J. A., Duncan, D. W., Koffolt, J. H. and Withrow, J. R. (1942): Packed Column and Plate Column Distillation Performance Correlation.
Holland, C.D. (1981) *Fundamentals of Multi Component Distillation* New York, McGraw- Hill
Jeronimo, M.A. and Sawistowskih, D.. (1973) : *Trans Institution Chemical Engineering*, 51 p. 265. London.
Kirachbaum, E. (1969) *Distillation and Rectification* Springer Verlag, Berlin.
Kister, H.Z. (1990) *Distillation Operations*, New York McGraw Hill
KISTER, H.Z. (1992) *Distillation Design*, New York, McGraw Hill.
Kister, H.Z. and Haas, J.R. (1990) *Chemical Engineering Progress* 86 (9) p 63.
Kister, H.Z., Larson, K.F., and Yanagi, T. (1994), *How do Trays and Packing Stack up? Chemical Engineering Progress*
Lemieux, E.J and Scotti, L.J. (1969) *Chemical Engineering Progress* 65 (3) P. 52
Mayfield, F.D., et al (1952) *Industrial Engineering Chemical* 4 p 9, 2238.
Perry, R. H. (2008), *Perry's Chemical Engineering Handbook*, 8th Edition, McGraw Hill
Smith, B.D. (1963) Design of Equilibrium State Processes, McGraw Hill.
Souders, M. Jr and Brown, G.G. (1934) Industrial Engineering Chemical 26 (1) p 96
Ujile, A. A. and Amagbo, L. G. (2013): Determination of plate efficiency of rectification column in refinery operations. *International Journal of Engineering and Technology, IJET* (3) 8 787 – 793.
Van, W. M. (1967) Distillation New York McGraw Hill.